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THE PETROLOGY OF THE CRETACEOUS GREYWACKES OF THE PURARI VALLEY, PAPUA

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[Read 13 November 1947]

Introduction

This petrological study of the Lower Cretaceous Greywackes of the Purari Valley, Papua, is based on six representative specimens supplied for the purpose by the Australasian Petroleum Co., with a view to comparing the Purari rocks with the Miocene greywackes of the Aure Trough (Edwards, 1947). The work was undertaken as part of the research programme of the Mineragraphic Section, of the Council for Scientific and Industrial Research, and is published by permission of the Council and of the Australasian Petroleum Co.

The Purari Formation consists of more than 5,000 ft. thickness of massive to thick-bedded sandstones, interstratified with thin bedded mudstones. The sandstones contain an occasional band of marine shelly fossils, with which are associated thin bands of shale with indeterminate land plant remains and silicified wood. The mudstones contain a meagre marine fauna. The rocks have been mapped and described by Carey (1945), and the specimens examined, which are numbered UP.82, 112, 116, 122, 125, 127 are from his collection, the localities of the specimens being shown by the corresponding numbers on his map. From an examination of a thin section of UP.112, he referred to the sandstones tentatively as greywackes, of tuffaceous origin.

The Greywackes*

The Purari greywackes are fine-grained grey rocks, that break into flat-sided blocks. The freshly broken surface has a ' salt and pepper ' appearance from the presence of innumerable small white felspar grains intermingled with darker matrix. The several specimens have a uniform even texture, broken only by a very occasional rock fragment about 1 mm. across. Though not apparent from the hand specimen the rocks are poorly sorted, as may be seen in thin section, and from the sizing analysis of Table 2. More than 30 per cent of the rock passes through a 325 mesh screen (aperture of 0·043 mm.). Of the sandy fractions about 65 per cent (50 per cent by weight of the rock) lies within a range of 0·05 to 0·15 mm. diameter.

Thin Sections

Examination of thin sections reveals that the greywackes consist essentially of angular grains of quartz, and felspars of various type, with lesser amounts of hornblende, chlorite, biotite, leucoxene, iron ores, glauconite, and minor accessory minerals, together with numerous minute fragments of sedimentary and igneous rocks, set in a prominent fine-grained argillaceous and chloritic matrix. The texture could be described as that of a micro-breccia. The bright green glauconite grains, though they constitute only about 1 per cent of the rock, are conspicuous in the thin sections. The relative proportions of the several major constituents vary somewhat with the specimen, as may be seen from Table 1, in which micrometric analyses of four Purari greywackes

* The term ' greywacke ' is used here in the sense defined in connection with the Aure sediments (Edwards, 1947).

are compared with those of two Aure (Miocene) greywackes. The most pronounced variation is the tendency for the proportion of felspar to increase where the quartz content declines. This is accompanied by a decrease in the proportion of matrix, which is most abundant in the quartz-rich specimens. The Purari greywackes contain much more quartz, and rather more felspar than the Aure rocks, and correspondingly less argillaceous matrix. They also have a lower content of ferromagnesian minerals.

Quartz constitutes from 5 to 15 per cent of the Purari greywackes. It occurs as clear angular grains, a number of which possess slender fragile projections. Many of the grains are fractured, and occasional grains are composite.

TABLE 1

MICROMETRIC ANALYSES OF PURARI GREYWACKES

Constituent	UP.116	UP.125	UP.122	UP.112	Aure Greywackes UK.797	UK. 1041
Quartz	15·1	10·5	4·6	6·3	tr.	0·1
Felspar	35·3	33·0	52·3	55·1	29·2	30·6
Hornblende (pyroxene) ..	2·5	3·0	4·1	3·9	9·1	11·9
Chlorite	5·6	3·0	3·7	5·1	—	—
Biotite (muscovite)	0·4	0·4	0·7	0·3	—	—
Glauconite ..	2·1	1·3	0·9	1·0	—	—
Iron ore and Leucoxene ..	2·0	1·4	2·5	3·1	—	—
Igneous Fragments ..	2·4	3·8	4·7	4·3	15·8	5·5
Sedimentary Fragments ..	6·3	5·6	6·7	5·5	4·2	1·3
Matrix	28·3	38·0	19·8	15·4	41·7	50·6

The felspar occurs as equally angular grains, and constitutes from 30 to 55 per cent (by volume) of the rock. The felspar is generally slightly cloudy, from partial alteration to kaolin, or less commonly, sericite; and in some instances the alteration is advanced. This feature readily distinguishes the felspar from the quartz in ordinary light. Several varieties of felspar are present. A proportion of the grains, commonly those most severely altered, are untwinned, and if favourably oriented, show a negative biaxial figure, so that this felspar is probably orthoclase. Some of the orthoclase is perthitic. Much of the felspar is plagioclase, with broad lamellar twinning, and less commonly zoning. A number of the plagioclase grains have straight extinction in the symmetrical zone, indicating that they consist of oligoclase (Ab_{80}). As many others have extinction angles in this zone of 15° to 20°, indicating that they consist of a more basic plagioclase, presumably an acid andesine (Ab_{50-55}). Some of the felspar fragments are enclosed within an irregular narrow rim of untwinned felspar; and in places these rims appear continuous around several adjacent, closely packed felspar grains, which suggests that the felspar of the rims is authigenic orthoclase or albite, deposited during diagenesis.

The conspicuous glauconite has the characteristic bright green colour of that mineral, and appears cryptocrystalline under crossed nicols. Many of the grains show shrinkage cracks. Some have a rounded form, but most of them are of irregular shape, and fill the interstices between other mineral grains, having been deformed while still gelatinous, during the compaction of the rock.

The hornblende is the greenish-brown form common to granitic rocks.

Some grains are well preserved, with angular form, but many are more or less altered to pale green chlorite.

The biotite occurs as crumpled elongate wisps, in some instances frayed apart along cleavage planes, and either wrapped round other grains, or infiltrated with matrix, or more commonly, partly altered to chlorite. More abundant than the fresh biotite are grains of more or less completely chloritized biotite, in which only a trace of the biotite remains. The glauconite may be derived from such altered biotite, but the transition stage is not often preserved. In addition to the biotite, there are occasional flakes of white mica.

The chlorite is a pale green to greenish-yellow variety, and occurs in three forms; as definite grains which represent altered biotite or hornblende, as minute particles disseminated through the matrix, and derived from the alteration of minute particles of ferromagnesian minerals originally in the matrix, and as a cement in the interstices between some of the coarser mineral fragments. It is probable that most of the chlorite is authigenic, the alteration of the original ferromagnesian minerals having occurred during diagenesis, and before the compaction of the rock.

Small irregular grains of opaque iron oxide minerals and of grey-white to pale buff leucoxene occur sparsely distributed through the rocks. The sections contain, in addition, occasional grains of zircon, apatite in both clear and fibrous or ' dusky ' forms, and tourmaline, and very occasional grains of colourless pyroxene, hypersthene, and epidote, the latter formed from the alteration of hornblende.

Irregular areas of sulphide minerals, probably marcasite, are present in some sections. The sulphide tends to form small concretions, cementing together the normal mineral grains of the rock.

Rock Fragments

Fragments of igneous rock, about the same size as the mineral fragments constitute up to 10 per cent of the rock (Table 1), but because of their small size and fine-grained character, they are not conspicuously different from the enclosing matrix.

Sedimentary and metamorphic fragments are the more abundant. They consist chiefly of a fine-grained graphitic schist, that resembles the fragments of schist found in the Aure greywackes, sericite or mica schist, mudstone, and an occasional fragment of extremely fine-grained quartzite or chert. The schist fragments are commonly lenticular, the long axis of the fragment, which is parallel to the plane of schistosity, being 2 to 5 times as great as the short axis. The mudstone and quartzite fragments are less aniso-dimensional. Some of the fragments are angular, but many are rounded.

The igneous fragments consist chiefly of extremely fine-grained extrusive rocks, apparently andesites. They consist of occasional small microphenocrysts of felspar or chloritized hornblende, in a base composed of fine laths of plagioclase and green chlorite. The plagioclase laths have nearly straight extinction, and are often sub-parallel. A few such fragments are stained brown, as from weathering. Other fragments consist of felspar laths in a greenish glassy base. In addition there are occasional grains of finely intergrown quartz and felspar, suggestive of granophyre, and others composed of several orthoclase crystals. Some are angular, others are rounded.

In general the rock fragments have the same dimensions as the associated mineral fragments, but occasional fragments are up to 0·5 mm. across.

Heavy Mineral Constituents

The heavy mineral constituents were extracted by suspension of the sized fractions of UP.125, and the unsized powders of UP.82 and UP.116 (crushed to pass 100-mesh), in acetylene tetrabromide (tetrabromethane) of sp.gr. 2·90. The heavy minerals other than hornblende, chlorite, biotite and glauconite were found concentrated in the 200-270 mesh and finer fractions.

The heavy minerals present, other than those just mentioned, are apatite, zircon, tourmaline, garnet, leucoxene, black iron oxides, rutile, pyroxenes, marcasite and (?)corundum.

The apatite occurs chiefly as idiomorphic prismatic crystals, or broken fragments of such crystals, but partly as water-worn and rounded grains. A variety of types are present. Many of the grains are colourless and water clear, in some instances with fine internal striations. Others are 'dusky' apatites, which contain numerous dark fibrous or rod-like inclusions, in parallel bundles, either in the core of the otherwise colourless crystal, or localized in part of it. In some crystals the inclusions are black, in others they are pleochroic from brown to black or purple. In yet other grains the crystal enclosing the fibres is itself coloured brown or purple, and is pleochroic ; and in some instances the inclusions are so closely crowded that the apatite grain appears almost opaque. Less commonly the apatite grains are strongly coloured brown or purple, and show strong pleochroism in these colours, but are free from visible inclusions. Such apatite can be mistaken for tourmaline.

In one specimen, UP.125, the apatite predominates almost to the exclusion of zircon, which tends to increase in the finer fractions. In the other two, the amount of zircon about equals that of apatite. The zircon is a colourless variety, and varies in shape from well-formed crystals or crystal fragments, to well rounded grains. There is no pink zircon, such as characterizes the Miocene greywackes of the Aure Trough.

Tourmaline is the third most abundant of the transparent heavy minerals, and in UP.125 is more abundant than the zircon. It is chiefly a brown variety, pleochroic to pale brown or colourless. There is also a little smoky grey-brown to blue tourmaline, and an occasional grain pleochroic from pink to green. Some grains have a prismatic outline, and some are angular, but commonly the tourmaline grains are well rounded, and some are practically circular in section.

Garnet is almost as abundant as tourmaline. It occurs as angular, and as rounded fragments. Some is colourless, some faint pink and some brown. The occasional grains of rutile are of two types, a foxy-red variety, and a yellow variety, the former being the more common. Most of the rutile grains are prismatic, or fragments of prisms, but some grains are rounded.

Pyroxene occurs as an occasional colourless grain with good cleavage and a high extinction angle (probably augite), and as a very occasional grain of hypersthene, pleochroic from pale green to faint pink. Epidote occurs as irregular yellow grains, and there is a very occasional grain of (?) corundum, with irregular blue areas in otherwise colourless grains.

Leucoxene is abundant, generally as somewhat waterworn grains, some of which contain relicts of the original ilmenite. The unaltered or only slightly altered opaque iron oxide minerals are still more abundant. Some grains consist of magnetite, because they jump to a hand magnet, others which do not are presumably ilmenite. In addition there are occasion small globular grains of iron sulphide (marcasite?).

The Crystalline Matrix

The matrix of the rock, which constitutes from 15 to 40 per cent of it, consists partly of chlorite, partly of finely divided quartz, felspar, sericite and other minerals together with rock fragments, and partly of grey opaque matter, presumed to be clay. In some sections minute grains of epidote occur through-out the matrix, associated with the chlorite. The chlorite in the matrix is authigenic, and derived from the alteration of the finely divided ferromagnesian minerals in the matrix during diagenesis. In places the chlorite occurs as finely disseminated particles of a size appropriate to such mineral fragments. Some of it, however, occurs as films cementing large mineral grains together. Such chlorite has a fibrous or columnar texture, the fibres all having their long axes normal to the surface of the cemented mineral grains. This chlorite has clearly been introduced to its present position during diagenesis. The greater part of the matrix appears, however, to be a primary component of the rock, rather than an introduced cement.

Grain Shape

The free mineral grains are highly angular, often with projecting corners, but apart from the schist fragments show little tendency towards elongation. A proportion of the felspar grains are elongated or prismatic in shape, but the majority are of irregular shape, with length and breadth not greatly different, so that they appear to be fragments of originally larger felspar grains. Similarly, a proportion of the quartz fragments are elongated splinters, but the majority of the grains are more or less equidimensional. The biotite and mica grains, on the other hand, and the schist fragments, show a pronounced tendency towards elongation, and tend to lie with their long axes parallel to the bedding planes of the rocks. Bedding is marked more by variation in proportion of mineral fragments and matrix, however, than by parallel orientation of elongated grains.

Grain Size and Degree of Sorting

Though friable, the majority of the specimens were sufficiently compacted and hard that they could not be broken down easily into their discrete grains. One, however, UP.125, tended to disintegrate when soaked in water and the resulting fragments could be disintegrated by pressing with the fingers under water, so it was selected for sizing. This was the specimen chosen also for chemical analysis, as more or less representative of the six specimens. The pulped sample was submitted to the Melbourne Ore Dressing Laboratory for

Table 2

Sizing Analysis of Purari Greywacke

Tyler Mesh	Aperture mm.	Purari Greywacke UP.125	Aure Greywacke UK.797
+ 14	1·168	—	0·6
+ 18	0·830	—	1·5
+ 28	0·589	—	3·5
+ 35	0·417	—	5·5
+ 48	0·295	0·7	6·5
+ 65	0·208	3·4	8·3
+100	0·147	9·5	11·9
+150	0·104	12·8	12·3
+200	0·074	24·1	11·5
+270	0·053	13·1	5·4
+325	0·043	1·8 }	33·0
−325	—	34·6 }	

sizing analysis. It was treated with a wetting reagent (Aerosol), and rolled in bottles for 12 hours. It was then wet-screened through 300-mesh and 325-mesh Tyler screens, and the oversize dried, and dry-screened on all screens over 300-mesh.

The sizing analysis is set out in Table 2, together with the sizing analysis of the most closely comparable of the Aure greywackes (UK.797), for comparison. This is the finest-grained of the Aure greywackes, and the results show that the Purari greywackes are still finer grained.

The Purari rocks are ill-sorted, in that they have a high content of argillaceous matrix (more than 30 per cent of the rock), in which respect they resemble the Aure rock. The sand fractions, however, are distinctly better sorted than the equivalent fractions of the Aure rocks. About 65 per cent of the sand-size grains (50 per cent of the rock) occurs in three adjacent fractions, the +150, +200 and +270 mesh fractions, with a range in aperture width of from 0·05 mm. to 0·15 mm., as compared with a spread over five adjacent fractions, with a range of 0·050 mm. to 0·30 mm. for the most comparable Aure greywacke. The average grain size of sandy grains in the Purari greywacke is 0·075 mm. diameter.

Specific Gravities

The specific gravities were determined for two specimens UP.116 and UP.125, and are given in Table 3. The determinations were made on powdered rock in a pycnometer, using 10 gram samples of the air-dried rock as submitted. The powders were immersed in distilled water at 10°C. in the pycnometer, and then evacuated with a hand pump until no renewed emission of bubbles could be detected on further reduction of the pressure.

A determination of apparent specific gravity of the uncrushed rock was made on a weighed lump of UP.125, by immersing the lump in a covered measuring cylinder containing distilled water, and noting the immediate displacement and subsequent displacement of the water. This gave a value of 2·36, as against 2·594 for the powdered rock.

Table 3

Specific Gravities, Absorption Ratios and Porosities of Purari Greywackes

Rock	Specific Gravity	Absorption Ratio	Porosity (dried at 110°C.)	Porosity (by immersion in measuring cylinder)
UP.116*	2·504	4·0	9·2	—
UP.125*	2·594	10·1	20·7	—
		10·2	20·9	—
UP.125†	2·36	—	—	20·0

* powdered rock † lump of rock

Porosities

The ratios of absorption and the porosities of UP.116 and UP.125 are also given in Table 3. In making these determinations, cuboid blocks of the naturally air-dried specimens were broken out of the specimens with a cold chisel, and weighed. The blocks were immersed in cold distilled water, and evacuated with a hand pump, after which they were left immersed under atmospheric pressure for 10 days. The specimens of UP.125 developed cracks and began to spall within half an hour of immersion, and the determination had to be concluded on the residual uncracked fragments of the original blocks. The surfaces were ' blotted ' with a dry towel, and the blocks weighed, after which they were dried in an air oven at 110°C. to constant weight.

A check determination on UP.125 was made by immersing a block cut to a near fit in a measuring cylinder, and noting the volume of water displaced at the moment of immersion, and at the end of ten days. As will be seen from

Table 3, the two methods gave a reasonable agreement. Specimen UP.116, which was more compacted than UP.125 had much the lower porosity, and it is thought unlikely that a rock with more than 30 per cent of fine matrix could have a true porosity as high as 20 per cent. It seems probable that a proportion of the moisture absorbed by UP.125 was taken up by the matrix minerals, and that the resulting expansion was responsible for the cracking and spalling of the rock.

Chemical Analysis

A chemical analysis of UP.125 was made by Messrs. Avery and Anderson, analytical chemists, and is set out in Table 4, together with an analys is of Aure greywacke, UK.1042, for comparison. The Purari greywacke is distinctly richer in SiO_2 and poorer in Al_2O_3, CaO, MgO and Na_2O than the Aure rock as befits its mineral composition. It contains much more FeO, and less Fe_2O_3, which is in keeping with the nature of its ferromagnesians, and more P_2O_5 and Cl as would be expected from its richness in apatite. It is rather richer in iron oxides, and poorer in MgO, CaO and Na_2O than most analysed greywackes; and it is probable that analyses of some of the other specimens, such as UP.112 or UP.122 would more resemble the Aure greywackes in composition, since they contain more felspar. However, the absence of basic plagioclase, which is the prevailing felspar in the Aure rocks, would militate against close similarity.

Table 4

Chemical Composition of Purari Greywacke

Component	Purari Greywacke UP.125	Aure Greywacke UK.1042
SiO_2	65·18	53·30
Al_2O_3	13·85	18·33
Fe_2O_3	1·30	2·41
FeO	5·43	2·36
MgO	1·87	2·62
CaO	0·72	5·88
Na_2O	1·48	2·18
K_2O	1·60	1·72
H_2O + 110°C.	3·94	3·14
H_2O − 110°C.	2·10	5·74
CO_2	tr.	1·00
TiO_2	0·90	0·84
P_2O_5	0·38	0·28
MnO	0·22	0·08
Cl	0·16	0·03
SO_3	0·90	0·08
	100·08	99·99

Analysts: Messrs. Avery & Anderson

Origin of the Greywackes

From the evidence of the rock fragments they contain, it is clear that the Purari greywackes are derived in part from sedimentary schists and mudstones, and in part from andesitic tuffs, or related rocks; but these rocks supplied only a small proportion of detritus. The bulk of the rock apart from the matrix, consists of grains of clear quartz, orthoclase and acid plagioclase, which appear to be fragments of originally larger grains of these minerals, so that in all probability the chief source rocks were granitic in character. The prevalence of common hornblende and biotite among the ferromagnesian components supports this, and so does the dusky apatite and tourmaline of the heavy constituents. Dusky apatite appears to form during the breakdown of basaltic hornblende in trachytic lavas (Edwards, 1938), but in the absence of such rocks is probably a reaction product of contaminated granitic rocks (Baker, 1941).

The chemical composition of the analysed Purari rock agrees with this interpretation of the rocks as largely resorted granitic material. The abundant well-shaped crystals of apatite, zircon and other minerals, among the heavy constituents also require an igneous source rock, whereas the well-rounded grains of these minerals are probably derived from older sediments. The minerals of the matrix are largely from the same general sources.

Conditions of Deposition

The occurrence of fossiliferous marine shell bands and of beds with plant remains such as *Sphenopteris*, coupled with grains of glauconite indicates that the sediments were deposited under marine conditions, close to a coastline. The massive bedded character of the rocks, coupled with freedom from current bedding, and their ill-sorted nature, as reflected by the association of a primary crystalline and clay matrix with sandy fractions, indicates that they were deposited by the discharge of sediment into still and relatively deep water (within the limits of the neritic zone). The presence of interbedded thin mudstone beds indicates that the supply of fine sediment was more or less continuous, while the supply of the more sandy fractions was occasionally interrupted. Finer fluctuations in the proportions of fine and coarse sediment being deposited are marked by a fine stratification, resulting from variations in the relative proportions of matrix and sand grains, that can be seen in some of the thin sections. The bands are of slightly different colour, darker bands corresponding to increased matrix, and are 1 to 3 mm. thick.

The unstable nature of the felspar and hornblende (labile components), and the angular form of the grains, points to rapid and vigorous erosion and transport from the source to the point of discharge, so that the conditions attending deposition are parallel to those deduced for the Aure greywackes. The finer-grained, and better-sorted character of the sand fractions in the Purari rocks, suggests, however, that either the detritus was transported a longer distance than the detritus of the Aure rocks, or under less vigorous conditions that permitted better grading, or else that the source material was of more uniform grain size than that which supplied detritus for the Aure greywackes. The abundant well formed apatite crystals in the heavy fraction suggests that much of the material was transported only a relatively short distance, in view of the extremely unstable nature of this mineral.

Comparison with the Aure Greywackes

Despite the general resemblance between the Purari and Aure greywackes, which is such that in the hand specimen the Purari greywacke might be mistaken for a fine-grained Aure greywacke, the petrological examination has revealed a number of distinctive differences as listed below :

1. The Purari greywackes are distinguished by the presence of glauconite, which does not occur to any extent in the Aure rocks.
2. The Purari rocks contain a notable amount of quartz, which is practically absent from Aure sediments of similar grain size.
3. The felspars in the Purari greywackes are orthoclase and acid plagioclase, in about equal proportions, whereas the felspars in the Aure greywackes are predominantly basic plagioclase, with little or no orthoclase. Moreover, the plagioclase grains in the Aure rocks are clearly the equivalent of felspar

phenocrysts of andesitic lavas, and tend to a lath-shaped form, whereas those in the Purari rocks appear to be fragments of originally coarser felspar crystals, derived from a granite or granodiorite.

4. The hornblende in the Purari greywackes is a common hornblende, such as might be found in a granitic rock, whereas the Aure rocks contain a variety of hornblendes such as are found in andesites, including basaltic hornblende.
5. Pyroxene is an unusual mineral in the Purari sediments, but is present in some abundance in many of the Aure rocks.
6. Fragments of igneous rock, chiefly a variety of andesites are a conspicuous component of the Aure rocks, whereas in the Purari rocks andesitic fragments are inconspicuous, and show much less variety of composition.
7. Practically every section of the Aure greywackes includes one or more sections of microfossils; microfossils are absent, or practically absent from the Purari rocks.
8. The heavy mineral suites of the two series are distinctive. In addition to glauconite, the Purari greywackes contain an abundance of apatite, including colourless, fibrous or 'dusky' and coloured forms, whereas the Aure rocks contain only a small amount of colourless apatite. The Purari rocks contain an abundance of tourmaline, whereas the Aure sediments contain only small amounts of tourmaline. The Aure rocks contain two varieties of zircon, a colourless zircon, which may be water worn, and a distinctive pink zircon, which nearly always has perfect crystal shape. The Purari greywackes, by contrast, contain only colourless zircons.

These differences, while they have great diagnostic value, arise from fortuitous differences in the terranes from which the two groups of sediment derived their material. They have little or no significance as regards the classification of the rocks.

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